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A PRECIPITATION CLIMATOLOGY FOR THE HYDROLOGIC SERVICE AREA OF NWSO NASHVILLE, TENNESSEE

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1. Introduction

After recently acquiring the Hydrologic Services Area (HSA) and associated duties and responsibilities for middle Tennessee, and the increased emphasis on hydrometeorology by the National Weather Service, the authors perceived the need to develop a precipitation climatology. Determining the normals and extremes of precipitation across the HSA and identifying weather patterns that produce heavy precipitation across middle Tennessee would be helpful in producing Quantitative Precipitation Forecasts (QPFs) by Nashville meteorologists and river stage forecasts by River Forecast Centers (RFCs).

With the main population centers of middle Tennessee concentrated along major rivers, climatology has shown that past heavy precipitation events have produced major flooding at many locations. With the spin-up of the NWSO Nashville HSA, the office has the responsibility to mitigate the loss of life and property caused by flooding in middle Tennessee. To accurately forecast river stages, the meteorologists at the local NWSO need to accurately forecast precipitation amounts which are used to determine river stage forecasts. Another important reason for the development of a precipitation climatology was to determine what constitutes a heavy precipitation event across middle Tennessee.

2. Data

The data used in this study were acquired from the National Climatic Data Center (NCDC) in Asheville, North Carolina. Maximum precipitation frequency information for the Nashville HSA was derived by extracting the greatest 24-hr totals from each cooperative station, ranking the totals, then computing maximum rainfall events for one, five, ten, and thirty year periods. Monthly and annual rainfall normals over a thirty year period with averaged values from 1961-1990 were used in this study from 15 cooperative stations across the Nashville HSA. These values were obtained from the *Climatography of the United States Series #81* paper published by NCDC.

Hourly precipitation data for the 15 cooperative stations, which have records covering a 30 year period, were obtained from NCDC. The stations were selected based on their spatial representation across the Nashville HSA and their continuous precipitation reports over the 30 year period. The U.S. Weather Bureau/NOAA Daily Weather Map series was used to classify the weather pattern which produced heavy rainfall over the Nashville HSA.

3. Topography

Figure 1 shows the cooperative stations within the HSA used in this study. Figure 2 shows the Nashville HSA, which extends west to east across middle Tennessee from the Tennessee River to the Cumberland Plateau region, and has significant variations in topography. Figure 3 shows the local topography in middle Tennessee.

The topography across middle Tennessee, beginning from the westernmost portions of the Nashville HSA, is a region of gently rolling plains sloping gradually from 200 to 250 ft above sea level in the west to about 600 ft in the hills overlooking the Tennessee River. The hilly Highland Rim, a wide circle touching the Tennessee River Valley on the west and the Cumberland Plateau on the east,

together with the enclosed Central Basin, makes up the whole of middle Tennessee.
The Highland Rim ranges from about 600 ft along the Tennessee River to 1,000 ft on its eastern edge and rises 300 to 400 ft above the Central Basin, which is a rolling plain of about 600 ft average elevation. A crescent of hills reaching to over 1,000 ft lies south of Nashville. The Cumberland Plateau, with an average elevation of 2,000 ft above sea level, extends roughly northeast to southwest across eastern-middle Tennessee in a belt 30 to 50 mi wide. It is bound on the west by the Highland Rim and overlooks the Great Valley of east Tennessee on the east. The vegetative cover across much of middle Tennessee is a mixture of deciduous and evergreen forests.

4. Normal Rainfall

It is important to have the knowledge of the normal monthly rainfall of the local area and its spatial distribution. Normal rainfall for a specific cooperative station is determined by averaging the past 30 years of data every ten years (i.e., 1941-1970, 1951-1980, 1961-1990, etc.). In this study, the normal rainfall for the entire Nashville HSA was determined by averaging the normal 1961-1990 monthly rainfall amounts of the 15 cooperative stations (Figs. 4 and 5). Owenby, et al. (1992) defined climatological normals as the arithmetic mean of a climatological element computed over a long time period. International agreements eventually led to the decision that the appropriate time period would be three consecutive decades (Guttman 1989).

Figure 5 indicates the average wettest month of the year across the Nashville HSA as March, with 5.7 in. December is second at 5.5 in, and October is the driest with 3.5 in. Gaffin and Lowry (1996) characterized dry and wet monthly periods for west Tennessee. For the Nashville HSA, similar findings were determined. Climatologically precipitation is fairly uniform throughout the year, although the five-month period from June through October (summer and into autumn) is considered the dry season, with only a third of the total annual rainfall occurring. The seven month period from November through May (late fall through spring) is considered the wet season, when two-thirds of the annual precipitation occurs across the Nashville HSA.

Normal precipitation increases from 48 in annually in northern-middle Tennessee, to 56 in across southwest-middle Tennessee. Average annual precipitation amounts also increase from 56 in along the northwest portions of the Cumberland Plateau region in middle Tennessee to 62 in across the southeast portions of middle Tennessee along the southern portion of the Cumberland Plateau (Fig. 4). This pattern of larger annual rainfall amounts to the south and east across middle Tennessee results from several factors.

Most synoptic weather systems generally move from west to east across middle Tennessee, with cold fronts aligned southwest to northeast. The Gulf of Mexico contributes to increased moisture, particularly across the southern portion of middle Tennessee, which is located closer to this source region. The higher precipitation amounts in the east are likely caused by orographic effects due to the Cumberland Plateau.

Monthly averaged precipitation amounts for the Nashville HSA were grouped together according to the four seasons of the year (according to the standard meteorological classification). December through February was classified as winter, March through May as spring, June through August as summer, and September through November as fall (Fig. 6 a-d).

During the winter months, (Fig. 6a), a large precipitation maximum in excess of 5.5 in during December and January, to between 5 and 5.5 in during February occurs across south-central Tennessee. The orientation of the Cumberland Plateau and the northeast-southwest alignment of synoptic weather systems across middle Tennessee closely coincides with the isohyets of maximum precipitation. Also, according to Gaffin and Lowery (1996), this is caused, in part, by developing low pressure systems over the Gulf of Mexico creating more rainfall across this area are they move northeastward.

For the spring months of March-May (Fig. 6b) the same large precipitation maximum in excess of 6.5 in during March, in excess of 5 in during April, and in excess of 5.5 in during May occurs across southeast-middle Tennessee. Again, the topographical features of the Cumberland Plateau and the orientation of synoptic scale weather systems from northeast-southwest across middle Tennessee contribute to the locations of maximum precipitation.

The summer months of June-August (Fig. 6c) show isohyets greater than 4 in during June and August, and greater than 5.5 in during July across eastern-middle Tennessee along the Cumberland Plateau. A minimum of synoptic scale frontal passages during summer across middle Tennessee accounts for the change in the orientation of the areas of maximum precipitation.

The fall months of September-November (Fig. 6d) show areas of maximum precipitation greater than 4.5 inches in September, greater than 4 inches in October, and greater than 5.5 inches in November across southeast-middle Tennessee. The alignment of these isohyets again reflects a more frequent occurrence of synoptic scale frontal systems during late autumn, and the topographical effects of the Cumberland Plateau.

5. Precipitation Frequency

As stated in Section 2, maximum precipitation frequency data were computed for each of the 15 cooperative stations across middle Tennessee for one, five, ten, and thirty year periods. The results were plotted as isohyets and are shown as Figs 7-10. The data show maximum 24-hr precipitation amounts.

The one year 24-hr maximum precipitation amounts show little variation across middle Tennessee, ranging from in excess of 3 inches in western-middle Tennessee, to less than 2.5 inches in eastern-middle Tennessee (Fig. 7). Five year 24-hr maximum precipitation amounts show a minimum of under 4 inches in eastern middle Tennessee, to a maximum of greater than 4.5 in across southwest-middle Tennessee (Fig. 8).

Ten-year 24-hr maximum precipitation amounts show a larger disparity. A minimum of less than 4 in is confined to extreme northeast-middle Tennessee, increasing to 5.5 in across southeast-middle Tennessee (Fig. 9). Finally, thirty year 24-hr maximum precipitation frequency values show a minimum of less than 5 inches in extreme southwest-middle Tennessee, while values greater than 8 in are located across south-central middle Tennessee (Fig. 10).

6. Meteorological Phenomena Inducing Heavy Precipitation Events

To determine a heavy precipitation event across middle Tennessee, a climatology of previous heavy precipitation events over 24-hr periods during the years 1961-1990 was derived. Using the charts from the *Rainfall Frequency Atlas of the U.S.* as a guide, it was determined that a 3 in precipitation amount within a 24-hr period would constitute a heavy precipitation event. It was then determined that a heavy precipitation event for the Nashville HSA would be amounts of 3 in or more within a 24-hr period at three or more cooperative stations across middle Tennessee. Using this criteria led to the extraction of 161 heavy precipitation events which occurred across the Nashville HSA during the period 1961-1990 (Appendix).

It was determined that at least three stations would have to meet the criteria of 3 in precipitation amounts over a 24-hr period to accurately show that each heavy precipitation event was the result of a large scale pattern and not an isolated event. The use of one-fifth of the 15 cooperative stations as a gauge for heavy precipitation events also effectively filtered out any incorrect precipitation data. After each 3 in precipitation event was extracted from the cooperative station CD-ROM for Tennessee covering the time period 1961-1990, the data was cross-referenced against the other stations to determine the 161 heavy precipitation cases documented in the attached Appendix.

The 161 heavy precipitation events were then classified according to the previous climatologies of heavy precipitation events completed over the central and eastern United States by Maddox, et al. (1979) and Crysler, et al. (1982). These studies provided guidance for making the determinations. Maddox, et al. (1979) studied 150 heavy rainfall occurrences and identified three primary types of heavy rainfall events. Junker (1992) also identified the three types of heavy rainfall events. These include synoptic, frontal, and meso-high. Due to tropical systems occasionally producing heavy rainfall across middle Tennessee, tropical events will be identified in this study.

Synoptic events were identified by Maddox, et al. (1979), Junker (1992), and Gaffin and Lowry (1996) as heavy rain events resulting from "an intense synoptic scale system," or slow moving system. Junker (1992) further stated that one of the primary ingredients for a synoptic event is "a strong 500 mb trough moving slowly east or northeast." Heavy rainfall associated with this type of system usually occurs in the warm sector ahead of the cold front and 500 millibar trough. Maddox, et al. (1979) found that "deep moisture was usually present with precipitable water values around 1.50 in." Junker (1992) stated that "synoptic events are most common across the southern portion of the United States from fall through early summer." Doswell, et al. (1996) indicated that there is an unmistakable connection between synoptic-scale weather systems and deep, moist convection. Doswell (1987) also suggested that "the connection is via the moistening and destabilization created by the modest but persistent synoptic-scale vertical ascent ahead of short-wave troughs."

Frontal events were defined by Maddox, et al. (1979) as heavy rain events occurring along or just north (near the 500 mb ridge) of a slow moving or stationary surface front usually oriented from west to east. These events occur primarily at night. Bonner (1966) also documented the nocturnal maximum in the low level jet as the forcing mechanism for frontal heavy rainfall events. Junker (1992) and Maddox, et al. (1979) found that upper level winds are usually found to parallel the front allowing convective cells to train over an area.

The mesoscale convective complex (MCC) and mesoscale convective system (MCS) have been shown by Maddox (1980), Fritch and Maddox (1981), and Maddox, et al. (1981) to develop nocturnally along a low level jet where extensive moisture transport occurs. Warm, moist air forced over a front will produce the heaviest rainfall on the cool side of the front and also primarily at night. Doswell, et al. (1996) further stated that "The well-known tendency for flash floods and heavy rainfall to occur after dark means that the convection can persist well into the night but usually dies off late in the morning of the next day. Redevelopment then occurs in the late afternoon. This allows the synoptic flow and diurnal heating to reaccumulate the needed ingredients for another round of convection."

Gaffin and Lowery (1996) and Maddox, et al. (1979) defined meso-high heavy rain occurrences as events that "occur in association with quasi-stationary thunderstorm outflow boundaries which are generated by previous convective activity. The heaviest rains usually occur near the 500 mb large scale ridge position and on the cool side of the surface boundary, usually to the south or southwest of the meso-high center." Maddox, et al. (1979) extensively studied mesoscale heavy rainfall events and found that meso-high events occurred approximately half the time east of a slow moving frontal band and are primarily nocturnal in nature. Doswell, et al. (1996) also noted that mesoscale processes such as the "role of mesoscale terrain, an important lifting mechanism when the flow is upslope," must be considered.

Mesoscale processes associated with MCSs can be responsible for heavy precipitation events in a number of ways. MCSs often produce large pools of outflow that persist for many hours after the rain-producing convection itself has dissipated. Such outflow boundaries often play a vital role in the initiation of subsequent convection, which may develop into a slow-moving MCS as described by Chappell (1986).

Tropically induced heavy rainfall events were also classified in this study. Schoner and Molansky (1956) and Junker (1992) stated that "the heaviest rainfall associated with a hurricane usually falls along the immediate coast but sometimes a lesser maximum occurs inland." Junker also noted the heaviest rainfall usually occurs slightly to the right of the track of the storm. The amount and areal extent of rainfall in a 24-hr period depends on the storm's forward speed, circulation size, and how the storm interacts with the westerlies. However, many storms are asymmetric and some, because of their structure, have more convection north and west of the storm. Examples of the intrusion of tropical moisture into middle Tennessee due to strong synoptic forcing were the landfalls of hurricanes Camille and Frederick. Both hurricanes produced damage and widespread flooding that cost millions of dollars and a number of lives along the Gulf of Mexico and South Atlantic coasts of the U.S. (Sugg, et al., 1971), (Powell 1982).

Junker (1992) indicated that "any time a hurricane or the remains of a hurricane interact with a system in the westerlies, a secondary maximum of precipitation is possible with the maximum sometimes exceeding the initial one that occurs at landfall."

7. Monthly Heavy Precipitation Averages

Of the 161 heavy precipitation events analyzed in this study, over half were classified as synoptic

(94 total events), approximately one-fourth (41) were frontal, whereas the remaining events were either meso-high (19) or tropical (7). Breakdowns of heavy precipitation events for the NWSO Nashville HSA are shown in the tables below. It is also important to compile frequency of heavy rainfall occurrences per number of years for the Nashville HSA to provide forecasters with thirty year climatological averages. These results are shown in Table 3.

Table 1. Heavy rainfall event types by season for the Nashville HSA

Event Type	Spring	Summer	Fall	Winter	Total
Synoptic	31	21	18	24	94
Frontal	8	19	10	4	41
Meso-high	1	13	5	0	19
Tropical	0	2	5	0	7
Total	40	55	38	28	161

Table 2. Heavy rainfall event types by month for the Nashville HSA

Event Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Synoptic	6	6	12	10	9	7	12	2	7	4	7	12
Frontal	1	0	3	2	3	10	5	4	7	2	1	3
Meso-high	0	0	0	0	1	2	5	6	5	0	0	0
Tropical	0	0	0	0	0	0	1	1	4	1	0	0
Total	7	6	15	12	13	19	23	13	23	7	8	15

Table 3. Frequency of heavy rainfall events by month as a function of number of years per event for the Nashville HSA

Event Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Synoptic	5	5	2.5	3	3.3	4.3	2.5	15	4.3	7.5	4.3	2.5
Frontal	30	>30	10	15	10	3	6	7.5	4.3	15	30	10
Meso-high	>30	>30	>30	>30	30	15	6	5	6	>30	>30	>30
Tropical	>30	>30	>30	>30	>30	>30	30	30	7.5	30	>30	>30

8. Conclusions

The purpose of this study was to depict a precipitation climatology of the NWSO Nashville, Tennessee HSA. One hundred and sixty-one heavy precipitation events were analyzed for a thirty year period from 1961-1990 using 15 cooperative stations strategically picked across middle Tennessee.

It was determined that mean annual precipitation ranges from around 48 in across northern middle Tennessee to 56 in across southwest-middle Tennessee, with a maximum of 62 in along the southern portion of the Cumberland Plateau over southeast-middle Tennessee. The Gulf of Mexico contributes to increased moisture, particularly across the southern portion of middle Tennessee, with the higher precipitation amounts in the east and southeast likely caused by orographic effects due to the Cumberland Plateau.

It was determined through extensive analysis of previous heavy precipitation events that a three inch precipitation amount in a 24-hr period would be considered a heavy rain. This determination correlates well with the NOAA document *Climatography of the United States No. 81,* for the Nashville HSA.

Other maximum precipitation averages calculated for one year, five years, ten years and thirty years show excellent correlations with the previously stated synoptic scale effects that occur across southwest middle Tennessee and the orographic lifting that likely enhances heavy rainfall across the Cumberland Plateau region in southeast-middle Tennessee.

Of the 161 heavy precipitation events in which three inches or more of precipitation occurred in a 24-hr period at three or more cooperative stations, 94 were defined as synoptic, 41 as frontal, 19 as meso-high, and 7 as tropical.

The mean distribution of precipitation across middle Tennessee for January through May also shows the same synoptic scale and orographic characteristics of heavy precipitation with heavier amounts increasing toward the southwest through east and southeast of the immediate Nashville area. This strongly correlates with the larger number of documented synoptic scale heavy precipitation events across middle Tennessee (Table 1). The mean distribution of precipitation across the Nashville HSA from June through September indicates a slight increase in amounts along the Cumberland Plateau due to the orographic effects along the windward side of the plateau. With the increase of synoptic scale heavy precipitation events in November and December, the mean distribution of precipitation again increases across southwest through southeast middle Tennessee.

Although normal monthly precipitation values cannot be directly used to compile a QPF, the trends these values show during the year, as well as geographic distribution, are significant. Forecasters must be aware of areas which receive more or less precipitation across the Nashville HSA. For these reasons, normal monthly precipitation has been included in this study.

The wet season for the Nashville HSA occurs from November through May, when analyzed synoptic and frontal events predominantly occur (Table 2). Gaffin and Lowery (1996) and Hoxit, et al. (1978)

found that "the maximum in rainfall frequency during the wet season was found to be slightly greater at night which could be the result of destabilization effects from cloud top radiation and cooling at middle and high levels, the diurnal cycle in boundary layer wind speeds and the evolution of mesoscale pressure systems generated by convective activity."

Although synoptic events occur during the summer months of June through August, there is a significant increase in frontal and meso-high events even into September. During the summer, there was found to be an increase in the frequency of solar-induced afternoon thunderstorms producing heavy precipitation. Tropical events occur during July through October, with four of the seven documented tropical events occurring in September. Heavy precipitation events were identified by month to assist forecasters at Nashville in determining trends in the type of heavy precipitation events that occur across the Nashville HSA.

One use of the data produced in this study involves the "intranet," an internal webpage using internet technology. This method allows the organization of a large amount of information which might otherwise prove too cumbersome to use operationally. The authors have posted their example for reference on the internet at *http://www.srh.noaa.gov/ftproot/ohx/html/qpfcli.htm.*

This type of climatological study may provide an example for other offices to follow in developing their own precipitation climatologies to document heavy precipitation trends and areas historically prone to heavy rainfall.

Appendix. Dates and classified types of heavy rain events across the Nashville HSA		
SYNOPTIC EVENTS		
Event Date	**Surface Feature**	**500 mb Pattern**
Mar 8/61	Warm front moving north (W-E)/cold front following surface trough	Deepening trough/sw flow (90 kt)
Jun 15/61	Cold front (N-S)	Trough/w flow (30 kt)
Jan 22-23/62	Cold front (N-S)	Deepening trough/sw flow (80 kt)
Feb 26-28/62	Warm front moving north (W-E)/cold front (N-S) and developing low following	Deepening trough/sw flow (80 kt)
Oct 2-3/62	Developing low along slow moving cold front (N-S)	Closed low/sw flow (60 kt)
Mar 5/63	Slow moving low along a quasi-stationary front (W-E)	Trough/sw flow (70 kt)
Mar 11-12/63	Quasi-stationary front (W-E)/cold front (N-S) following	Trough/sw flow (115 kt)
Mar 17/63	Warm front moving north (W-E)/cold front (N-S) following	Closed low/sw flow (60 kt)
Apr 30/63	Warm front moving northeast (W-E)/with cold front (N-S) following	Trough/sw flow (70 kt)
Aug 13/63	Warm front moving north (W-E)/cold front (N-S) following	Trough/w flow (35 kt)
Aug 29/63	Warm front moving northeast (N-S)/cold front (N-S) following	Trough/w flow (30 kt)
Jul 30/64	Cold front (N-S)	Trough/nw flow (30 kt)
May 27/65	Surface trough/cold front (N-S) following	Closed low and deepening trough/sw flow (60 kt)
Jul 3/65	Warm front moving north (N-S)/cold front (N-S) following	Trough/nw flow (50 kt)
Jul 2/66	Surface low	Trough/w flow (40 kt)
Dec 9/66	Cold front (N-S)	Trough/sw flow (60 kt)
Mar 6/67	Cold front (N-S)	Trough/sw flow (60 kt)
Dec 18/67	Developing low along cold front (N-S)	Trough/sw flow (85 kt)
Mar 12/68	Low pressure along slow moving cold front (N-S)	Closed low/sw flow (95 kt)
Mar 17/69	Cold front (N-S)	Cold front (N-S)/w flow (30 kt)
Jun 15/69	Cold front (N-S)	Trough/w flow (30 kt)
Nov 19/69	Cold front (N-S)	Trough/sw flow (110 kt)

Event Date	Surface Feature	500 mb Pattern
Dec 29-30/69	Cold front (N-S)	Trough/sw flow (80 kt)
Sep 9/70	Cold front (N-S)	Closed low/sw flow (80 kt)
Dec 22-23/70	Cold front (N-S)	Trough/sw flow (90 kt)
Feb 22/71	Low pressure with cold front (N-S)	Closed low/sw flow (100 kt)
Jul 30/71	Developing low along slow moving cold front (N-S)	Trough/sw flow (40 kt)
Oct 16/71	Slow moving low pressure along quasi-stationary front (W-E)	Closed low/w flow (30 kt)
Apr 22/72	Cold front (N-S)	Closed low/sw flow (85 kt)
Jul 5/72	Cold front (N-S)	Trough/sw flow (60 kt)
Jul 27-30/72	Quasi-stationary front (W-E)/ slow moving developing surface low	Trough/w flow (35 kt)
Sep 30/72	Cold front (N-S)	Trough/w flow (60 kt)
Apr 20/73	Cold front (N-S)/ developing surface low	Closed low/sw flow (70 kt)
May 27-28/73	Cold front (N-S)/ squall line	Closed low/sw flow (95 kt)
Jul 26/73	Cold front (N-S)/squall line	Trough/sw flow (40 kt)
Nov 27-28/73	Cold front (N-S)	Trough/sw flow (115 kt)
Dec 26/73	Slow moving cold front (N-S)/developing surface low	Trough/sw flow (90 kt)
Jan 10-11/74	Cold front (N-S)	Trough/sw flow (90 kt)
Jun 2/74	Cold front (N-S)	Trough/sw flow (30 kt)
Sep 26/74	Developing low along stationary front (W-E)	Closed low/w zonal flow (40 kt)
Dec 24-25/74	Warm front (W-E) moving north/cold front (N-S) later	Trough/sw flow (70-80 kt)
Feb 23/75	Developing low along slow moving cold front (N-S)	Closed low/sw flow (90 kt)
Jul 20/75	Slow moving cold front (N-S)/squall line	Trough/sw flow (20 kt)
Mar 21/76	Cold front (N-S)	Trough/sw flow (110 kt)
Jun 30/76	Slow moving cold front (N-S)	Closed low/w zonal flow (50 kt)
Mar 4/77	Slow moving cold front (N-S)	Closed low/sw flow (70-80 kt)
Mar 12/77	Low pressure along cold front (N-S)	Closed low/sw flow (115 kt)
Apr 3-5/77	Warm front moving north (W-E)/squall line to the south	Trough/sw flow (70-80 kt)
Oct 25/77	Cold front (N-S)	Trough/sw flow (50 kt)
Dec 3-4/78	Surface trough (N-S)	Closed low/n flow (20 kt)

Event Date	Surface Feature	500 mb Pattern
Dec 8-9/78	Cold front (N-S)	Closed low/sw flow (80-90 kt)
Jan 1/79	Cold front (N-S)	Closed low/sw flow (90 kt)
Apr 1-2/79	Cold front (N-S)	Trough/sw flow (85 kt)
Apr 12/79	Cold front (N-S)/low pressure	Closed low/sw flow (60 kt)
May 3-4/79	Slow moving cold front (NE-SW)/low and squall line to the south w/ cold front (N-S)	Trough/sw flow (75 kt)
Sep 21-22/79	Slow moving cold front (N-S)/low pressure	Trough/w zonal flow (50 kt)
Dec 12-13/79	Slow moving cold front (N-S)/low pressure	Trough/sw flow (70 kt)
Mar 17/80	Cold front (N-S)/ squall line	Trough/sw flow (70 kt)
Mar 20-21/80	Cold front (N-S)/low pressure	Closed low/sw flow (90- 100 kt)
May 17-18/80	Cold front (N-S)	Trough/sw flow (40 kt)
Jun 29/80	Cold front (N-S)	Trough/nw flow (50 kt)
Jan 3-4/82	Cold front (N-S)	Closed low/sw flow (120 kt)
Dec 26/82	Cold front (N-S)	Closed low/sw flow (50 kt)
Apr 5-6/83	Slow moving cold front (N-S)	Closed low/sw flow (50 kt)
May 18-19/83	Warm front (W-E) moving north/cold front (N-S) following	Closed low/sw flow (60 kt)
Jun 7/83	Cold front (N-S)	Closed low/sw flow (40 kt)
Nov 28/83	Cold front (N-S)	Closed low/sw flow (100 kt)
Apr 22/84	Warm front (W-E) moving north/cold front (N-S)	Closed low/sw flow (90 kt)
Apr 28/84	Cold front (N-S)	Closed low/sw flow (65 kt)
May 6-8/84	Stationary front (W-E)/low pressure	Closed low/sw flow (80 kt)
Jul 16/84	Slow moving cold front (N-S)	Trough/sw flow (30 kt)
Jul 27/84	Slow moving cold front (N-S)	Trough/sw flow (40 kt)
Sep 26/85	Slow moving cold front (N-S)	Trough/sw flow (70 kt)
May 28-29/86	Surface trough/low pressure	Closed low/sw flow (30 kt)
Jul 2/86	Slow moving cold front (N-S)	Closed low/sw flow (40 kt)
Nov 8-9/86	Cold front (N-S)/squall line	Trough/sw flow (70 kt)
Dec 9/86	Cold front (N-S)	Closed low/sw flow (90 kt)
Nov 9-10/87	Slow moving cold front (N-S)/low pressure	Trough/sw flow (90 kt)
Jan 19-20/88	Low pressure system	Trough/sw flow (90 kt)

Event Date	Surface Feature	500 mb Pattern
Sep 24/88	Developing low pressure along slow moving cold front (N-S)	Trough/sw flow (40 kt)
Nov 4-5/88	Warm front moving north (W-E)/cold front (N-S) following	Closed low/sw flow (100 kt)
Nov 19-20/88	Cold front (N-S)	Trough/sw flow (60 kt)
Jan 11-13/89	Cold front (N-S)	Trough/sw flow (60 kt)
Feb 13-15/89	Warm front moving north (W-E)/cold front (N-S) following	Deepening trough/sw flow (70 kt)
Feb 20-21/89	Cold front (N-S)	Trough/sw flow (110 kt)
Feb 4-6/89	Developing low pressure along slow moving cold front (N-S)	Closed low/sw flow (80 kt)
Apr 4/89	Cold front (N-S)/low pressure	Trough/sw flow (70 kt)
Jun 15/89	Developing low pressure along slow moving cold front (N-S)	Closed low/sw flow (60 kt)
Sep 14/89	Developing low pressure along slow moving cold front (N-S)	Closed low/sw flow (40 kt)
Oct 1-2/89	Developing low pressure along quasi-stationary front (W-E)	Closed low/s flow (50 kt)
Feb 3-4/90	Quasi-stationary front (N-S) ahead of cold front (N-S)	Trough/sw flow (80 kt)
May 16-17/90	Cold front (N-S)	Trough/sw flow (60 kt)
Jul 12/90	Slow moving cold front (N-S)	Trough/w flow (30 kt)
Dec 22-23/90	Low pressure along cold front (N-S) approaching from west	Closed low/sw flow (60 kt)

FRONTAL EVENTS		
Event Date	**Surface Feature**	**500 mb Pattern**
Apr 10-11/62	Quasi-stationary front (W-E)/ developing low pressure	Weakening trough/sw flow (65 kt)
Sep 16/62	Quasi-stationary front (W-E)	Trough/nw flow (30 kt)
Jul 12/64	Quasi-stationary front (W-E)	Trough/w flow (30 kt)
Aug 15-16/64	Quasi-stationary front (W-E)	Trough/sw flow (40 kt)
Sep 28-29/64	Quasi-stationary front (N-S)	Trough/sw flow (40 kt)
May 13/67	Quasi-stationary front (W-E)	Ridging/sw flow (75 kt)
May 15/67	Quasi-stationary front (W-E)	Trough/sw flow (70 kt)

Event Date	Surface Feature	500 mb Pattern
Jul 27/68	Quasi-stationary front (W-E)/ developing low pressure	Trough/w flow (35 kt)
Nov 27-28/68	Quasi-stationary front (W-E)/ developing low pressure	Ridging/sw flow (55 kt)
Jun 23-24/69	Quasi-stationary front (W-E)	Trough/sw flow (50 kt)
Jun 20-21/70	Quasi-stationary front (W-E)	Trough/w flow (40 kt)
Aug 20/70	Quasi-stationary front (W-E)	Trough/nw flow (30 kt)
Sep 5/70	Quasi-stationary front (W-E)	Trough/nw flow (30 kt)
Sep 18/70	Quasi-stationary front (W-E)	Trough/w flow (40 kt)
Apr 4/71	Quasi-stationary front (W-E)	Trough/sw flow (40 kt)
Jun 28/72	Quasi-stationary front (W-E)	Trough/nw flow (50 kt)
Jul 16/72	Quasi-stationary front (W-E)	Trough/w flow (40 kt)
Oct 18-19/72	Quasi-stationary front (W-E)	Trough/w flow (70 kt)
Dec 9-10/72	Quasi-stationary front (W-E)	Trough/sw flow (100 kt)
Mar 15-16/73	Quasi-stationary front (W-E)	Closed low/sw flow (70 kt)
Aug 23/74	Quasi-stationary front (N-S)	Trough/sw flow (20 kt)
Mar 12-14/75	Quasi-stationary front (W-E)/developing low pressure	Ridging/sw flow (70 kt)
Mar 28-29/75	Warm front moving north (W-E) becoming quasi-stationary	Closed low/sw flow (50 kt)
Sep 7/77	Stationary front (W-E)/developing low pressure	Trough/sw flow (35 kt)
Sep 25-26/77	Stationary front (W-E)/developing low pressure	Closed low/w zonal flow (40 kt)
Oct 8/77	Warm front (W-E) moving north/cold front (N-S) following	Closed low/w zonal flow (70 kt)
Jan 7/79	Warm front (W-E) moving north/developing low pressure	Trough/sw flow (70 kt)
Jun 21/79	Quasi-stationary front (NE-SW)	Trough/w flow (30 kt)
Jul 8/79	Slow moving warm front (W-E)/developing low pressure	Trough/w flow (20 kt)
Sep 5/80	Quasi-stationary front (W-E)	Trough/w flow (20 kt)
May 19/81	Quasi-stationary front (N-S)	Trough/w zonal flow (50 kt)
Jun 6-7/81	Quasi-stationary front (W-E)	Trough/w zonal flow (40 kt)
Aug 31-9/1/82	Dissipating warm front (W-E)	Trough/nw flow (20 kt)

Event Date	Surface Feature	500 mb Pattern
Jun 4/83	Quasi-stationary front (N-S)	Trough/w zonal flow (40 kt)
Jul 27/86	Warm front (W-E) moving north	Trough/sw flow (20 kt)
Dec 25/86	Warm front (W-E) moving north/low pressure followed by cold front (N-S)	Trough/sw flow (70 kt)
Dec 24-26/87	Strong warm front (W-E) ahead of slow moving cold front (N- S)	Closed low/sw flow (50 kt)
Jun 2/89	Quasi-stationary front (W-E)	Trough/sw flow (30 kt)
Jun 4/89	Quasi-stationary front W-E)	Trough/sw flow (40 kt)
Jun 6/89	Quasi-stationary front (W-E)/developing low pressure	Trough/nw flow (30 kt)
Jun 9/89	Quasi-stationary front (W-E)/low pressure	Trough/nw flow (30 kt)

MESO HIGH EVENTS		
Event Date	**Surface Feature**	**500 mb Pattern**
Jun 9/61	Surface trough	Trough/nw flow (30 kt)
Sep 1/61	Low pressure along surface trough	Trough/w flow (30 kt)
Jun 11/62	Thunderstorm outflow boundary	Trough/sw flow (25 kt)
Sep 13-14/62	Surface trough (N-S)	Trough/nw flow (30 kt)
Sep 7/71	Thunderstorm outflow boundaries	Trough/sw flow (20 kt)
Jul 8/74	Thunderstorm outflow boundary	Closed low/w flow (20 kt)
Aug 25/76	Thunderstorm outflow boundary	Trough/sw flow (30 kt)
May 28/78	Surface trough (N-S)	Closed low/n flow (20 kt)
Aug 11/78	Thunderstorm outflow boundary	Trough/w flow (20 kt)
Jul 22-23/80	Slow moving surface trough (N-S)	Trough/w flow (20 kt)
Jul 26/80	Thunderstorm outflow boundary	Trough/w flow (20 kt)
Aug 18/81	Stationary front (W-E)	Trough/sw flow (20 kt)
Aug 16-17/82	Surface trough (N-S)	Trough/sw flow (20 kt)
Jul 1-2/83	Surface trough (N-S)	Trough/w flow (20 kt)
Aug 29/84	Thunderstorm outflow boundary	SW flow (20 kt) along anticyclone to the east
Sep 3-5/86	Slow moving surface trough (N-S)	Trough/sw flow (25 kt) along anticyclone to the east
Jul 13-14/88	Surface trough (N-S)	Trough/nw flow (20 kt)

Event Date	Surface Feature	500 mb Pattern
Aug 20/88	Quasi-stationary front (W-E)	SW flow (20 kt)
Jul 8/89	Thunderstorm outflow boundary	Trough/sw flow (30 kt)

TROPICAL EVENTS		
Event Date	**Surface Feature**	**500 mb Pattern**
Sep 13-14/79	Low pressure (Frederick remnants)/cold front (N-S) following	Closed low/se flow (50 kt)
Sep 13-14/82	Low pressure (Chris remnants)	SW flow (20 kt)
Aug 16-17/85	Low pressure system (Danny remnants)	Trough/sw flow (50 kt)
Jul 1-3/89	Slow moving low pressure (Allison remnants)	Closed low/w flow (30 kt)
Sep 22-23/89	Slow moving low pressure (Hugo remnants)	Closed low/sw flow (30 kt)
Sep 26/89	Surface trough (Hugo remnants)	Closed low/sw flow (30 kt)
Oct 16-17/89	Slow moving low pressure system (Jerry remnants) along cold front (N-S)	Trough/sw flow (60 kt)

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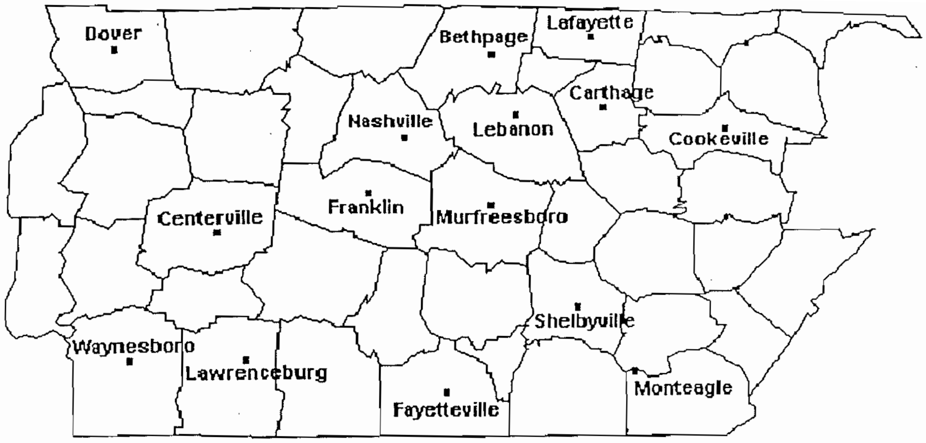

Figure 1. Cooperative stations used in this study.

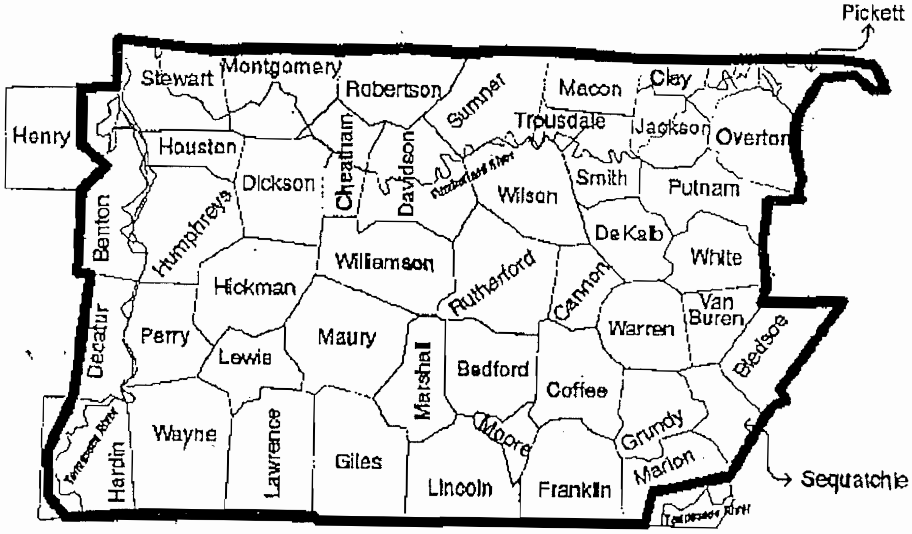

Figure 2. NWSO Nashville, Tennessee Hydrologic Service Area.

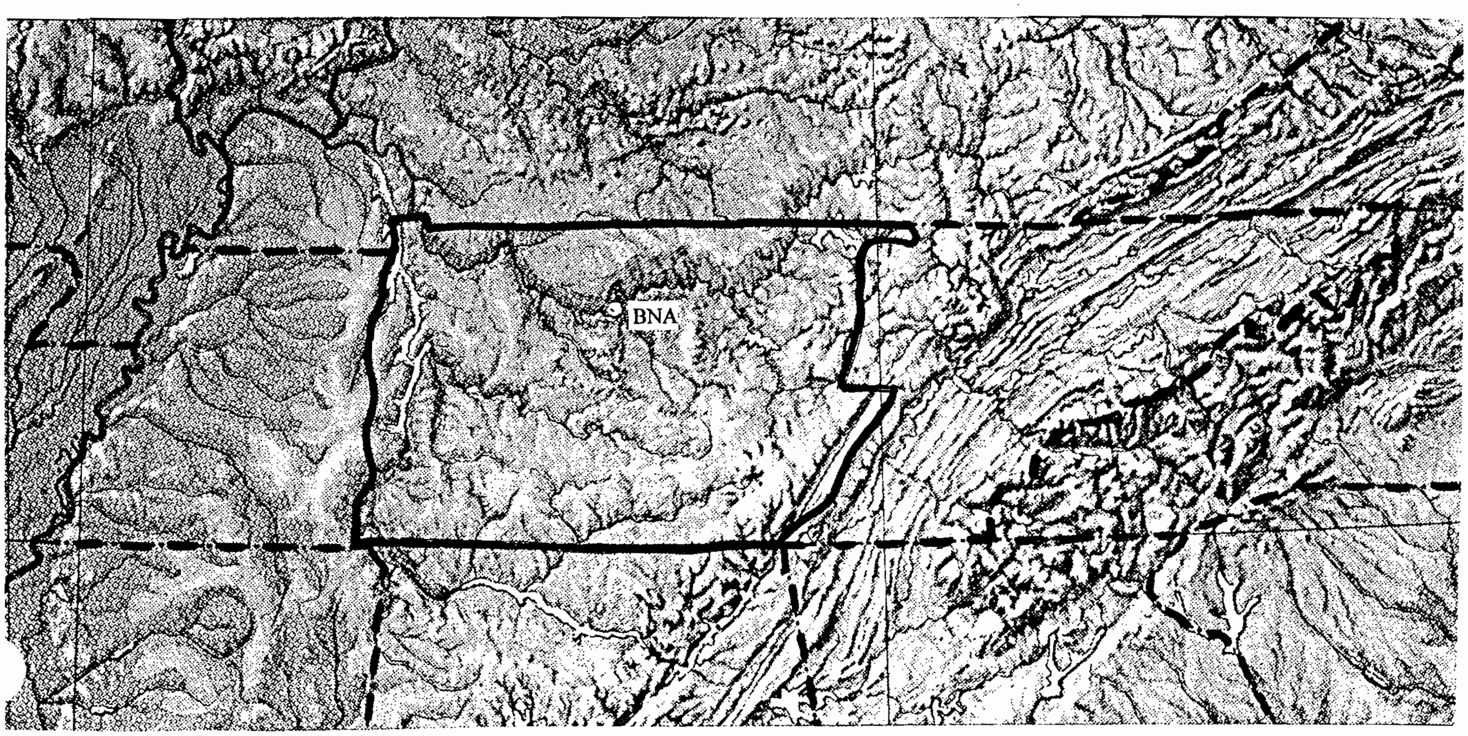

Figure 3. Topographic relief map of middle Tennessee. Nashville HSA outlined with solid line.

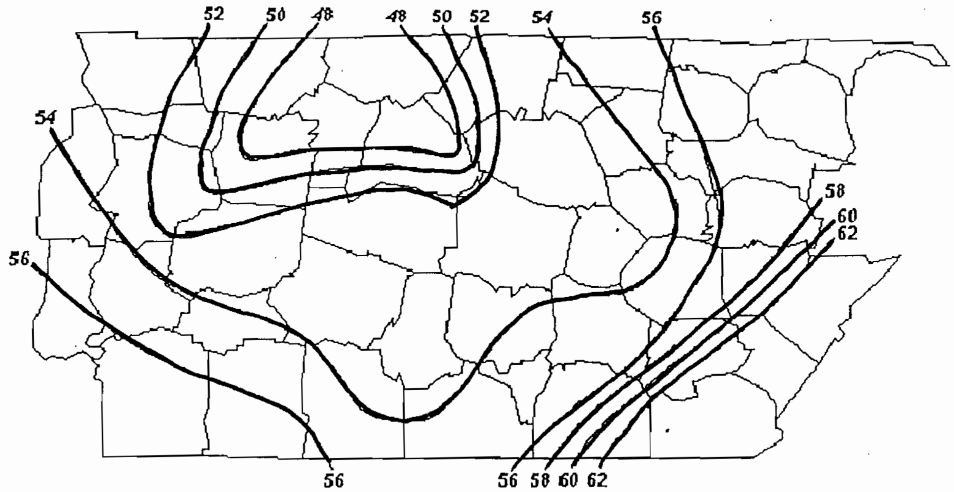

Figure 4. Average annual precipitation distribution (inches) across middle Tennessee using the data set.

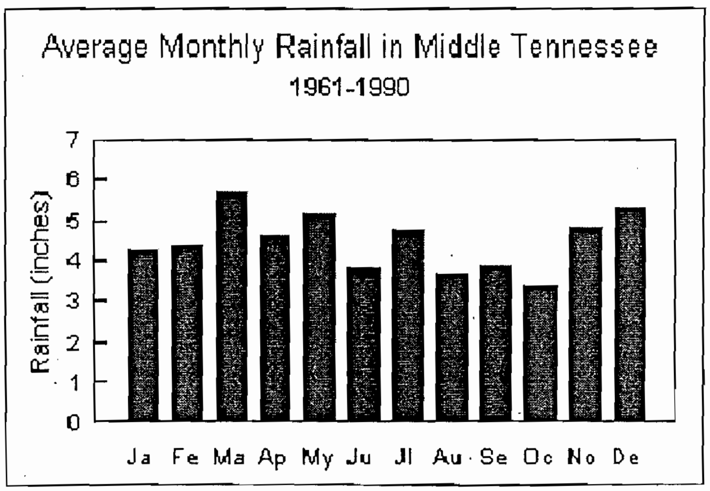

Figure 5. Average monthly distribution of precipitation in middle Tennessee using the data set.

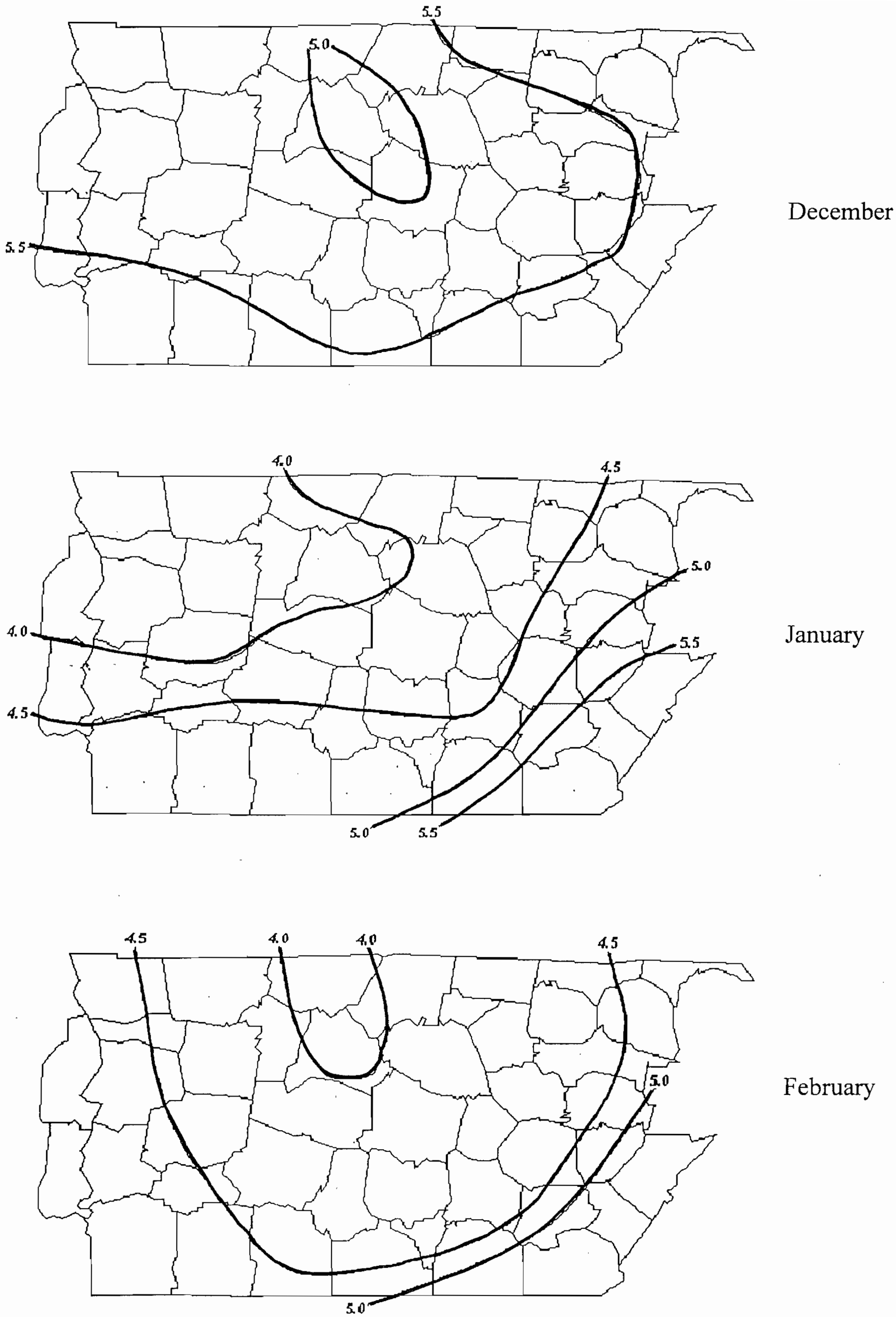

Figure 6a. Average precipitation in middle Tennessee for winter months using the data set.

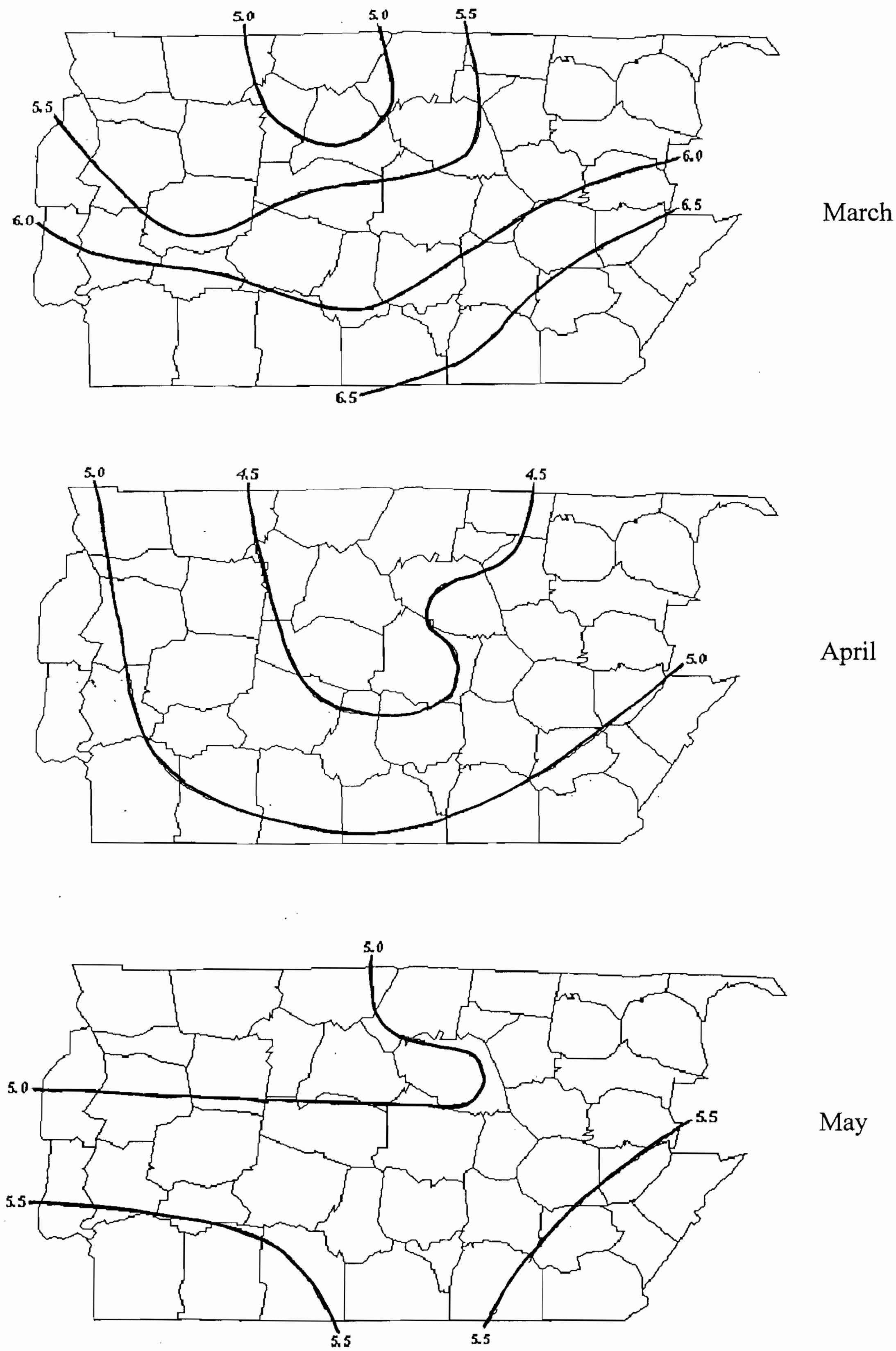

Figure 6b. Average precipitation in middle Tennessee for spring months using the data set.

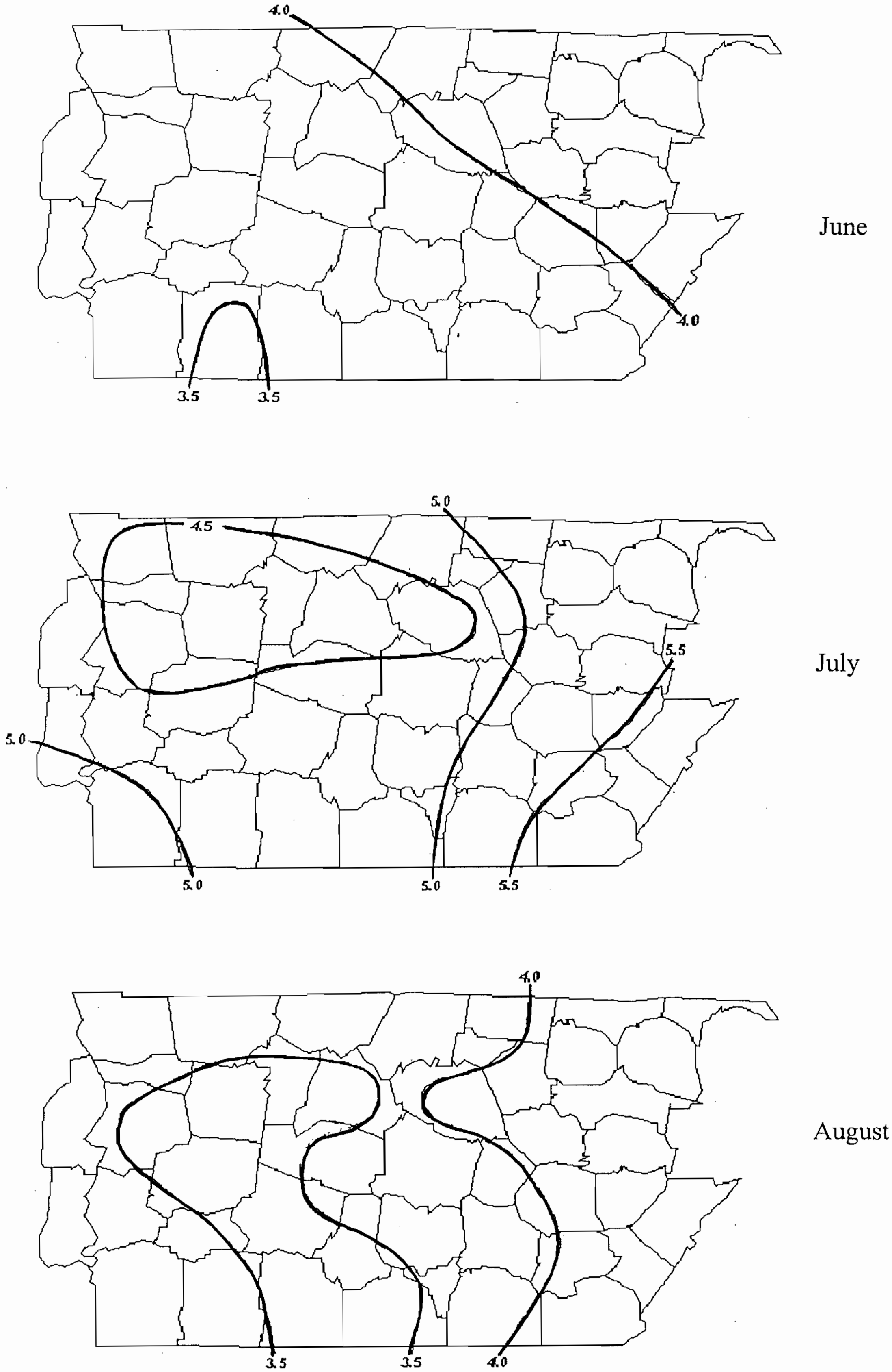

Figure 6c. Average precipitation in middle Tennessee for summer months using the data set.

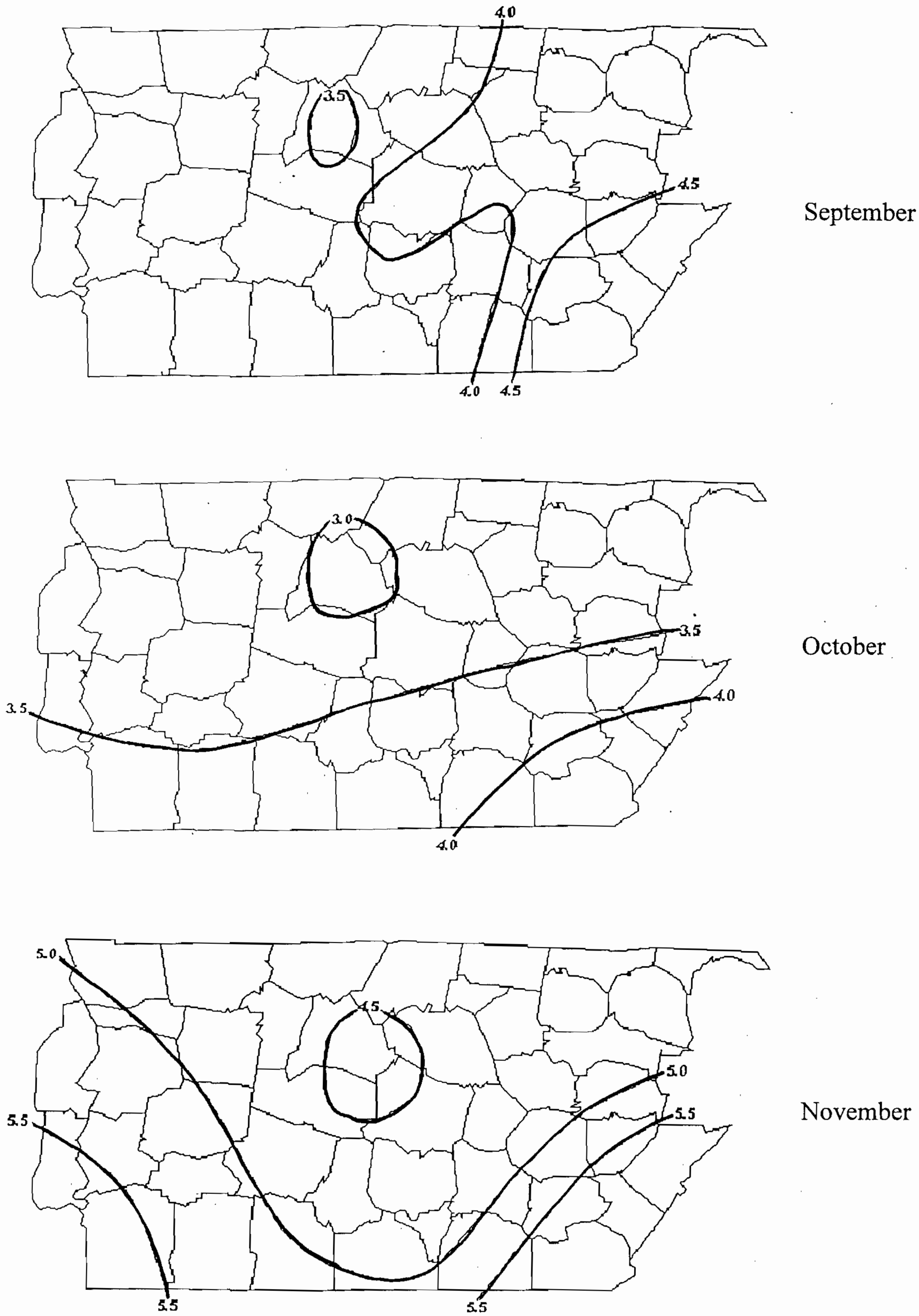

Figure 6d. Average precipitation in middle Tennessee for fall months using the data set.

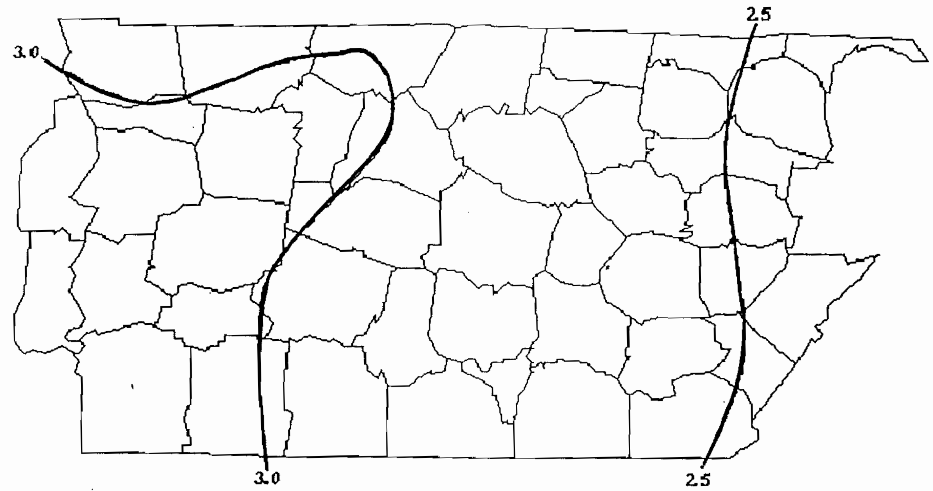

Figure 7. One year maximum rainfall (in) for 24-hr period for the data sets.

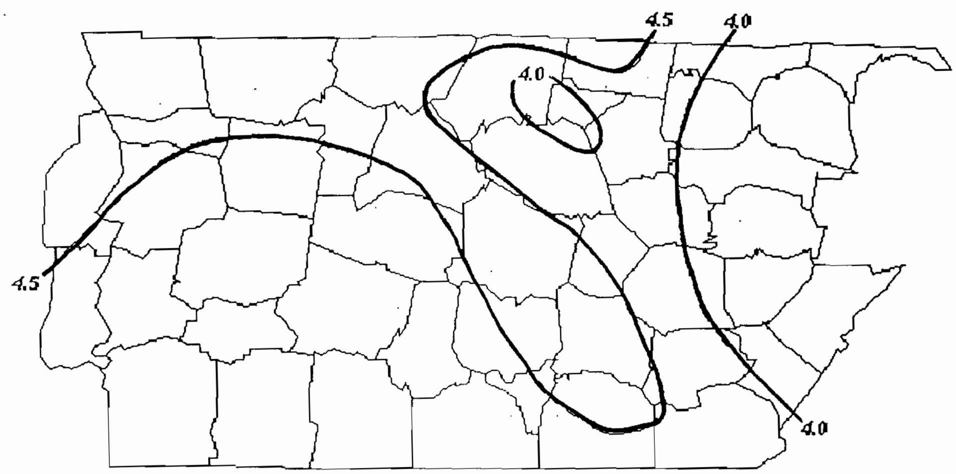

Figure 8. Five year maximum rainfall (in) for 24-hr period for the data sets.

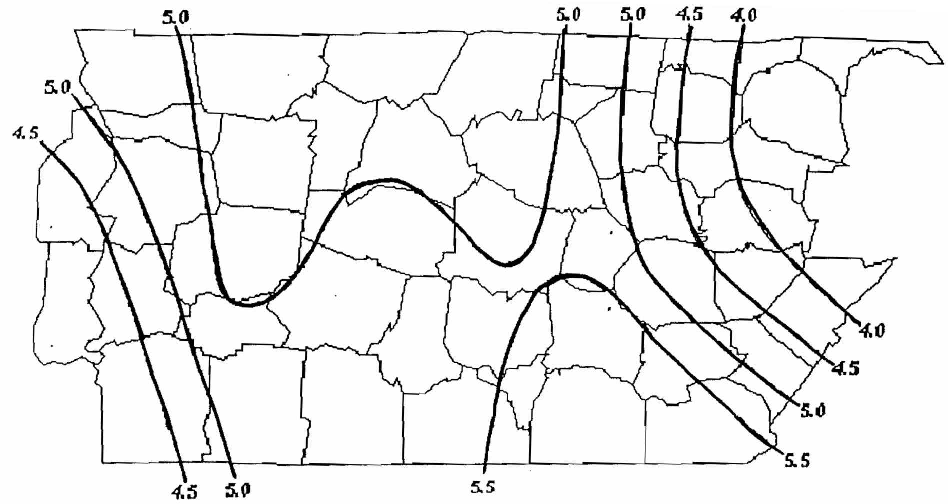

Figure 9. Ten year maximum rainfall (in) for 24-hr period for the data sets.

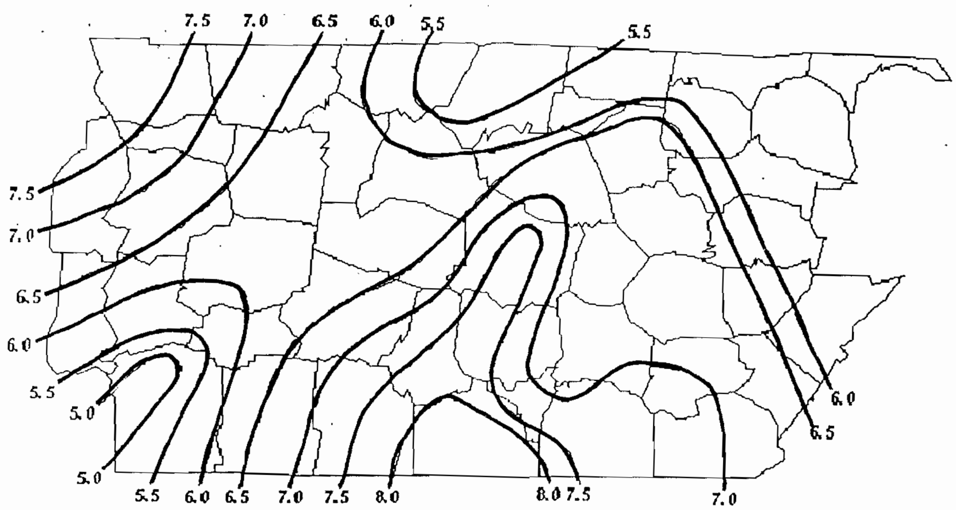

Figure 10. Thirty year maximum rainfall (in) for 24-hr period for the data sets.